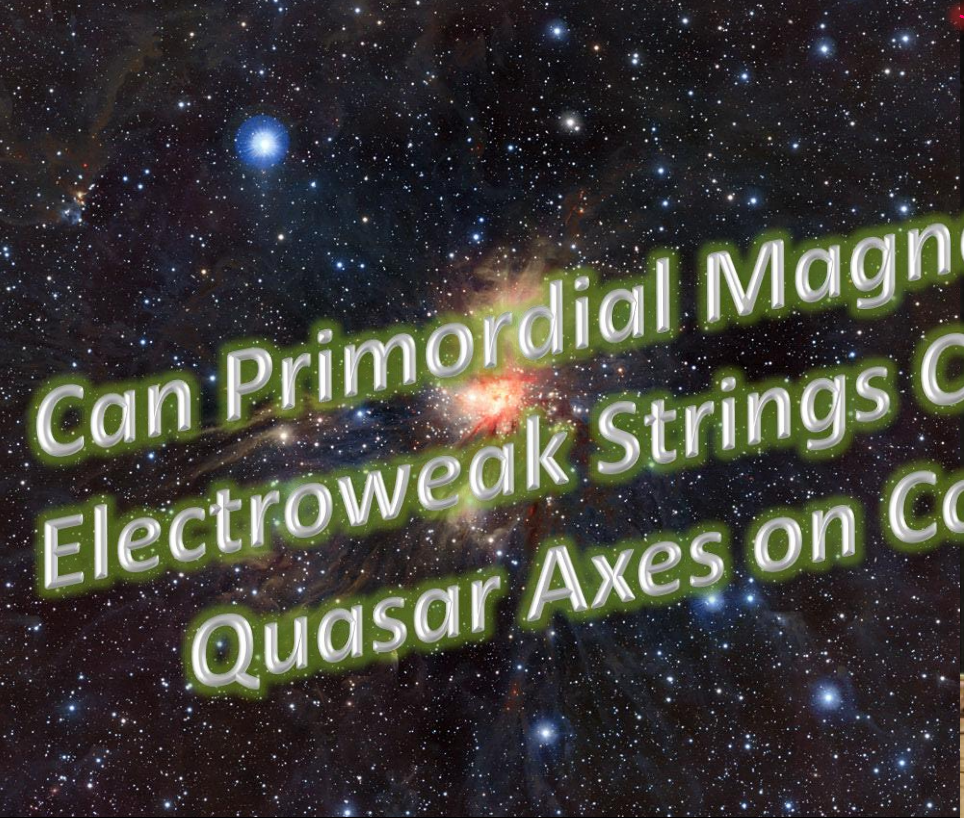
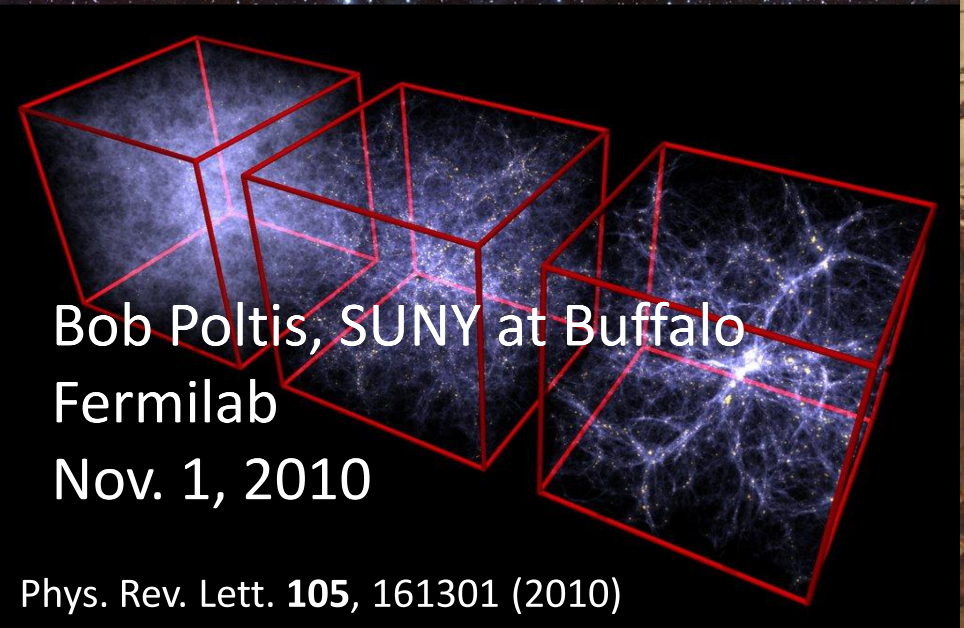
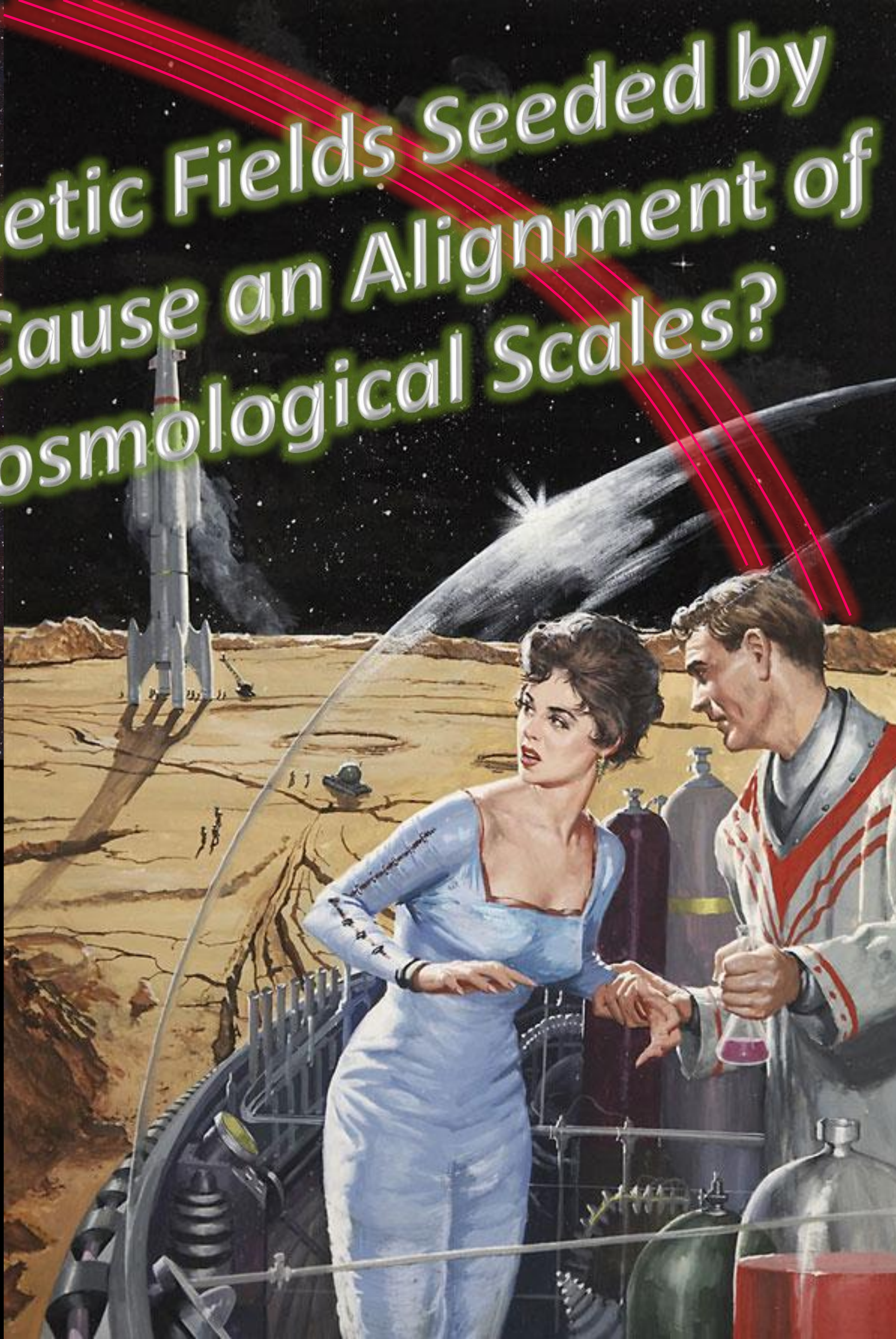
Can Primordial Magnetic Fields Seeded by Electroweak Strings Cause an Alignment of Quasar Axes on Cosmological Scales?







Bob Poltis, SUNY at Buffalo

Fermilab

Nov. 1, 2010

Phys. Rev. Lett. **105**, 161301 (2010)

Motivation

- Quasars are distant, mysterious objects
  - discovered in the late 1950's
  - debate over their nature as recently as the 1980's
- Cosmic strings are predicted by many theories, but have never been observed
- The origin of primordial magnetic fields is still unknown

Outline

Cosmic strings

Quasars

Effect of magnetic fields on structure formation

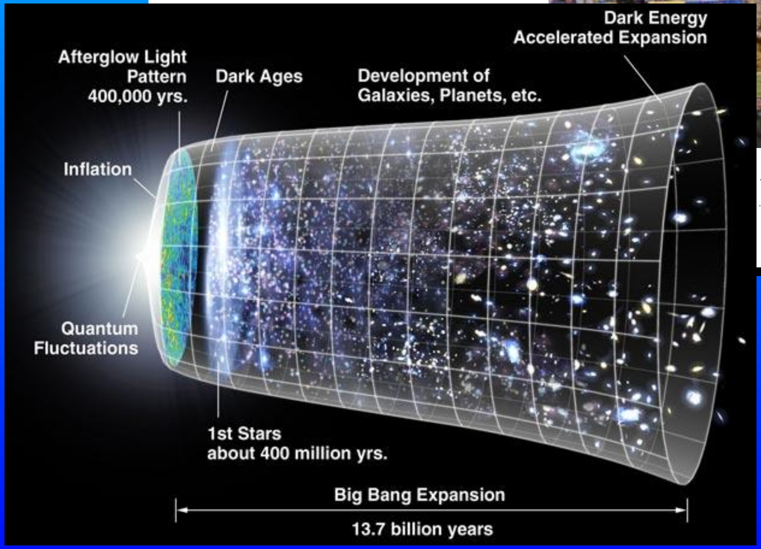
The observation

Match model with observation

Cosmic Strings

Start at the beginning: the Big Bang.

The *observable* universe can't be larger than it's age (~13.7 billion years)



The (currently) observable universe extends out ~13.7 billion LY* in every direction.

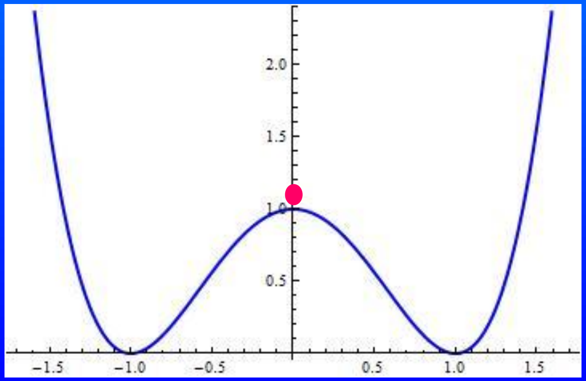
When the universe was much younger, the size was much smaller.

Cosmic Strings

Why are they interesting/not crazy?

Not the same strings as string theory

Strings and other defects form when a symmetry is broken



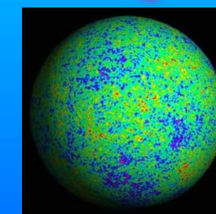
At the top of the hill, the symmetry is unbroken. When the field settles at a bottom of the potential, the symmetry is broken.

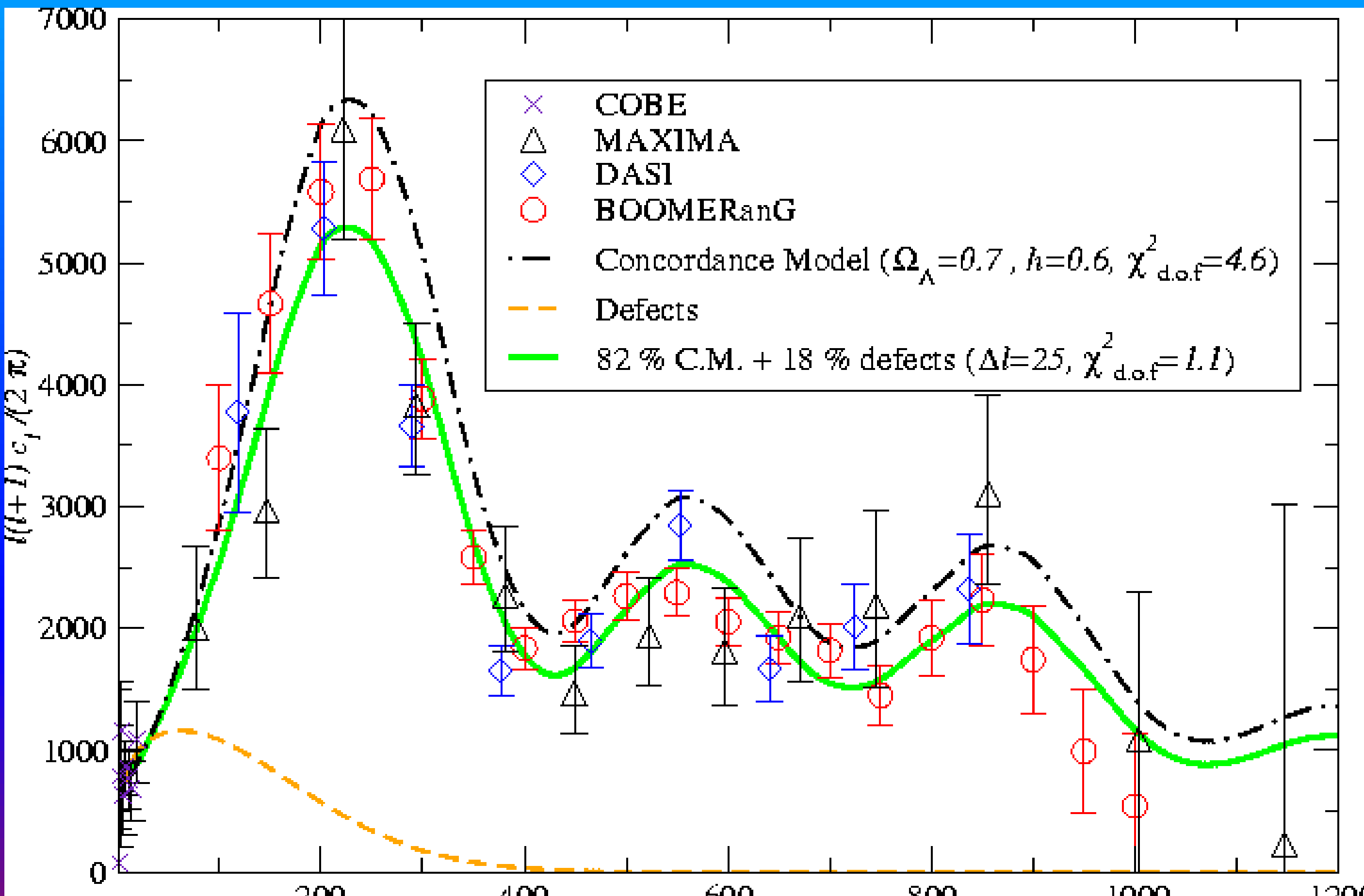
Cosmic Strings

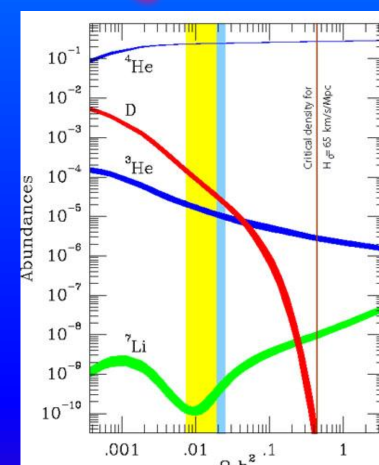
Don't destroy the universe.

Well-behaved relic from the early universe

The earliest times we can probe:
Directly ~350,000 yrs.
Indirectly ~ 200 sec .







Defects

Electroweak cosmic strings are linear defects from the electroweak phase transition when the universe was 10^{-10} s old.

An analogy to a defect is domains in ice crystals as water freezes.

Cosmic Strings

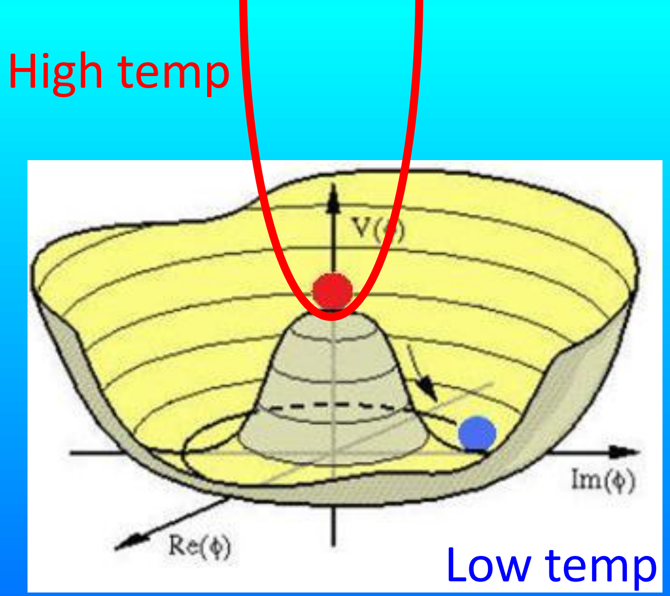
Ex: Abelian Higgs model

$$\mathcal{L} = \frac{1}{2}\left(D_\mu \Phi\right)^2 - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} - V$$

$$V = \lambda\left(\Phi^2 - \frac{\sigma^2}{2}\right)^2$$

Break the U(1) symmetry. U(1) means the elements of the group (here Φ) are the set of 1x1 unitary matrices.

Cosmic Strings



$$V = \lambda\left(\Phi^2 - \frac{\sigma^2}{2}\right)^2$$

In the hot early universe $|\Phi| = 0$.
As the universe cools, different disconnected regions of space (randomly) assume different minima of the potential.

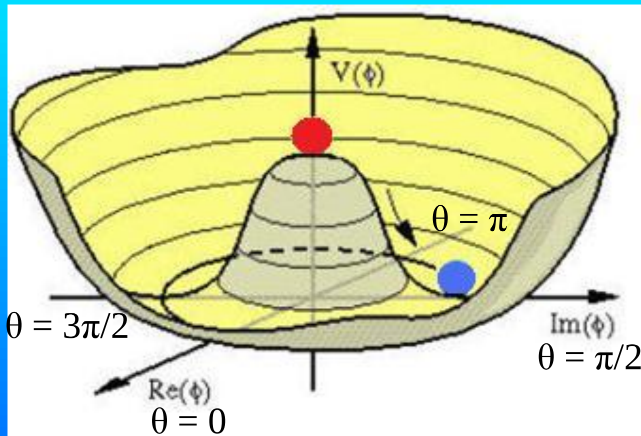
The vacuum energy only cares about $|\Phi|$

☞ Φ may be complex

$$\langle\Phi\rangle = \frac{\sigma}{\sqrt{2}}\exp(i\theta)$$

The only requirement is Φ be single valued and smoothly varying everywhere in space.

Electroweak Cosmic Strings



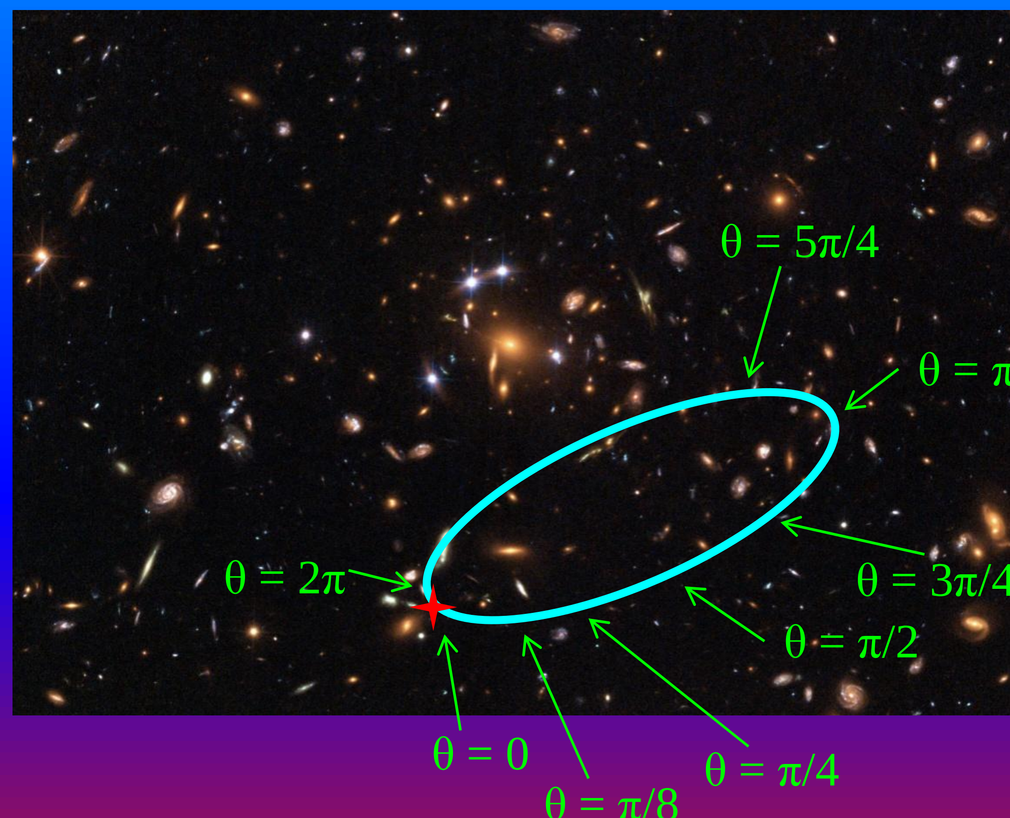
$$V = \lambda\left(\Phi^2 - \frac{\sigma^2}{2}\right)^2$$

Φ must be single-valued and smoothly varying everywhere in space.

$$\langle\Phi\rangle = \frac{\sigma}{\sqrt{2}}\exp(i\theta)$$

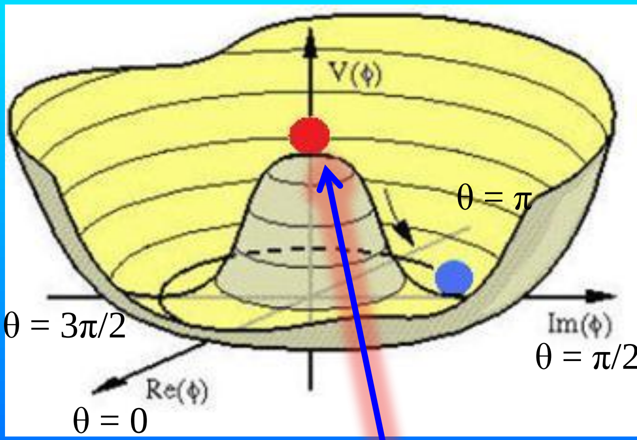
$\Phi = (\sigma/\sqrt{2})\exp[i0]$
$\quad = (\sigma/\sqrt{2})\exp[i2\pi]$

The field is still single-valued.



Cosmic Strings

$$\langle \Phi \rangle = \frac{\sigma}{\sqrt{2}} \exp(i\theta)$$

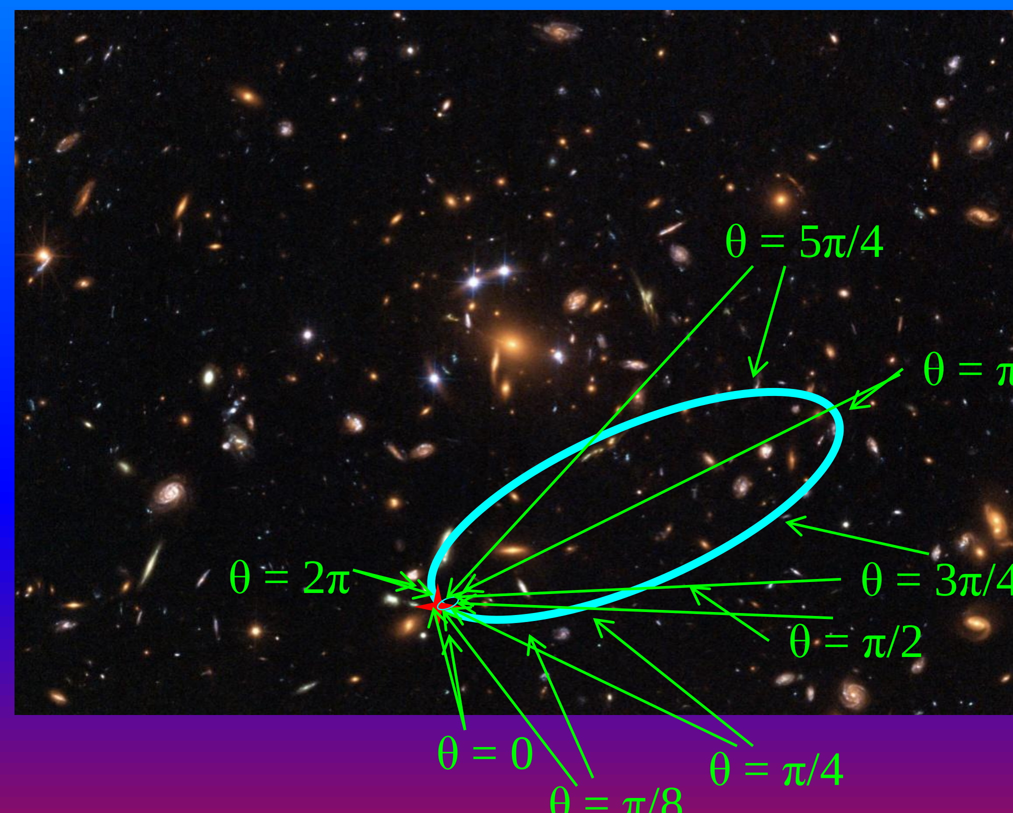


Now shrink the path down to a point.

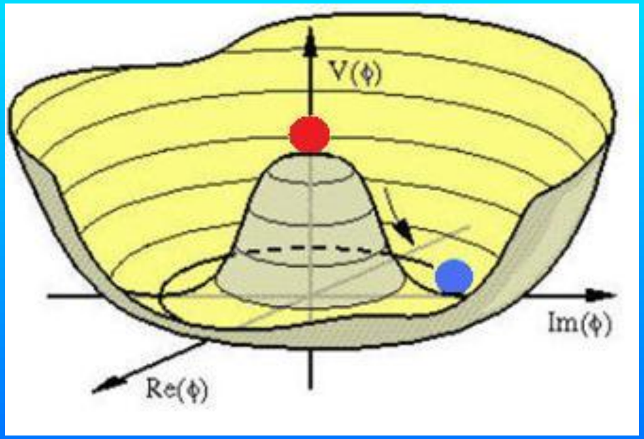
As we shrink the closed path down, there must be a point somewhere within the path where the phase θ is undefined.

The phase θ is undefined when the field takes on the value Φ = 0.

Somewhere within our closed loop the symmetry is restored.



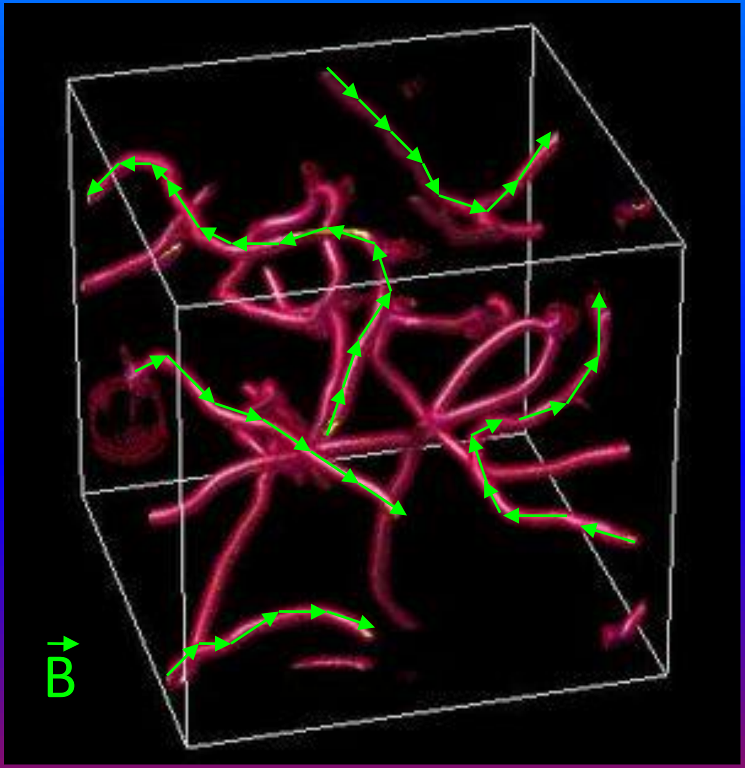
Cosmic Strings



Electroweak strings also contain:

Structure: “wiggles”

Lines of magnetic flux that lie along the length of the string



Cosmic Strings

Strings come in 2 varieties:

The early universe should have produced many of these long thin defects. So where are they now?

Infinitely long strings are stable ☺

…but…

…most models predict only a few such strings exist in the visible universe.

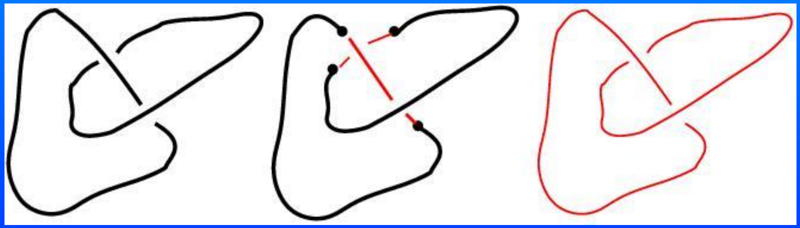
→Very hard to find!

Cosmic Strings

Loops of electroweak cosmic string may decay away by gravitational radiation.

Strings may also be broken.

These defects may also exist in interesting configurations…we consider two interlinked loops of string.

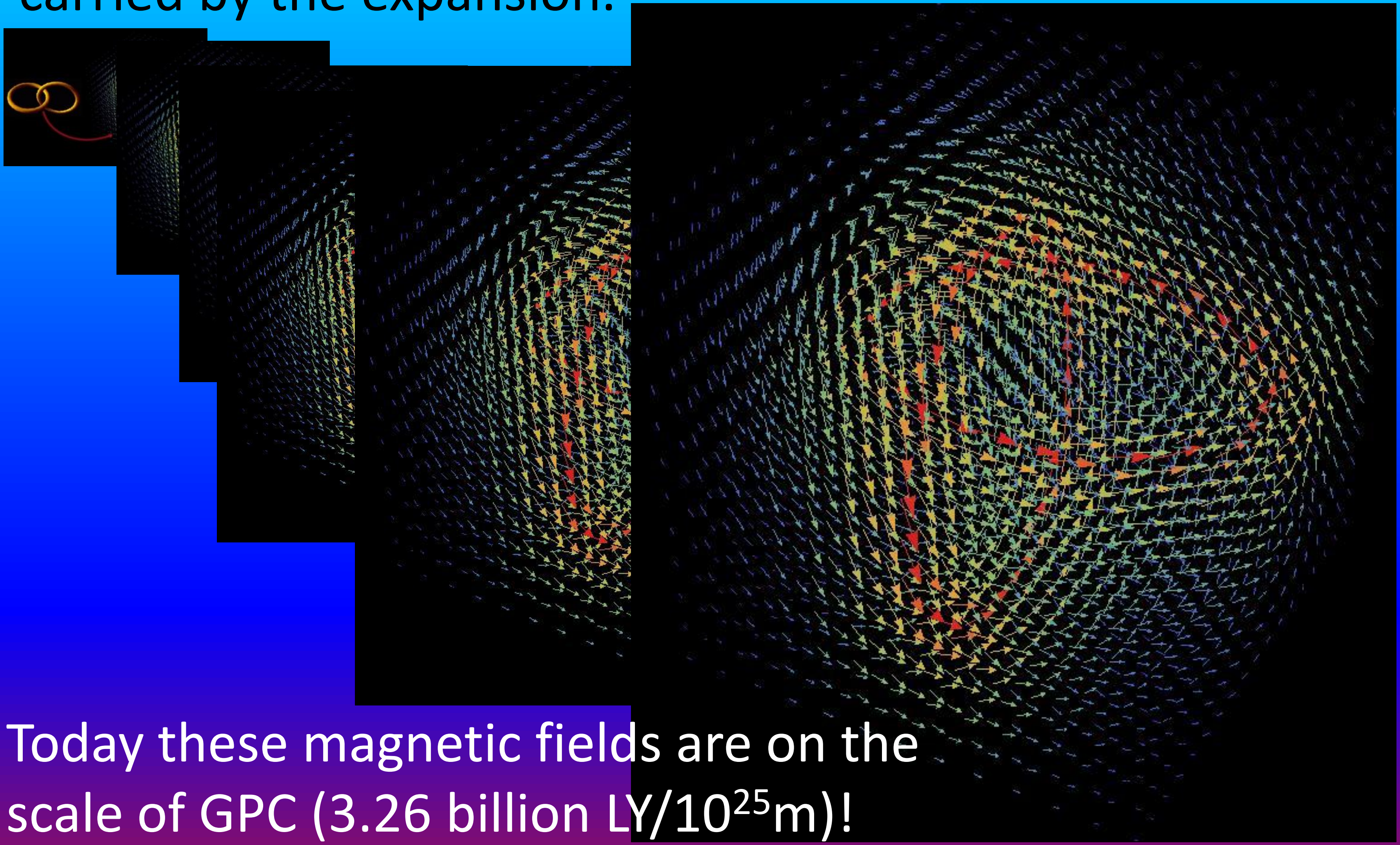


Tension in the string will collapse the string.

Because this process takes place in the (highly conducting) plasma of the early universe, the magnetic field will be left over: imprinted into the plasma of the early universe.

Cosmic Strings

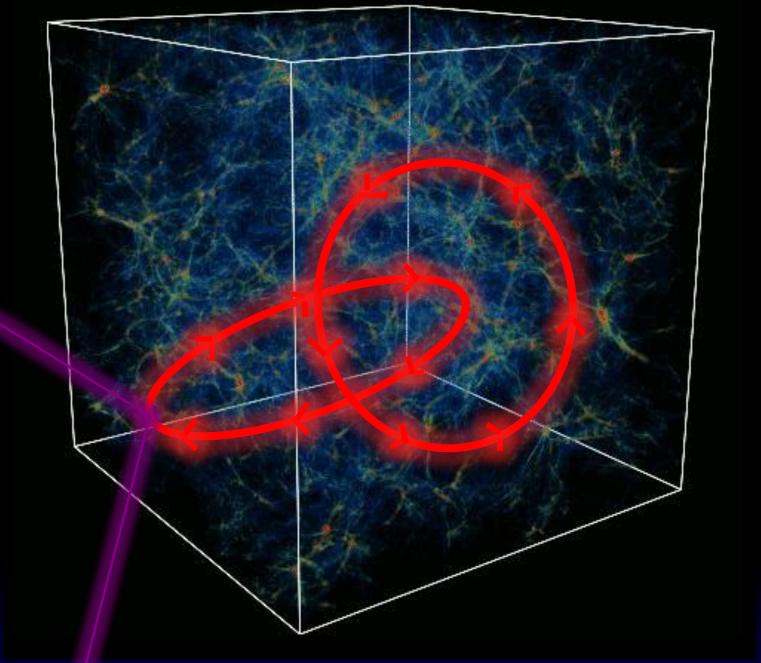
The magnetic field imprinted into the universe will be carried by the expansion.



Today these magnetic fields are on the scale of GPC (3.26 billion LY/10^{25}m)!

What Is Observed

On “small” scales the magnetic field is approximately uniform.



On (very) large scales the structure of the linked magnetic fields becomes visible.

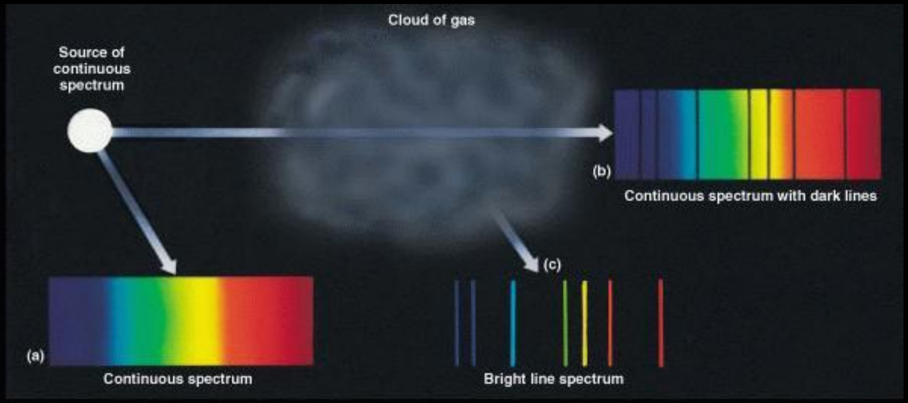
Quasars: Small, Bright, and Far Away

- Size is comparable to solar system scales
- Energy output is comparable to energy output of entire galaxies
- Because they are in active *forming* galaxies, they exist(ed) when the universe was ~1billion years old .

Quasar Structure

Quasars may be grouped into three types based on their spectral features:

- BAL show broad absorption lines
- NAL show narrow absorption lines
- No absorbers

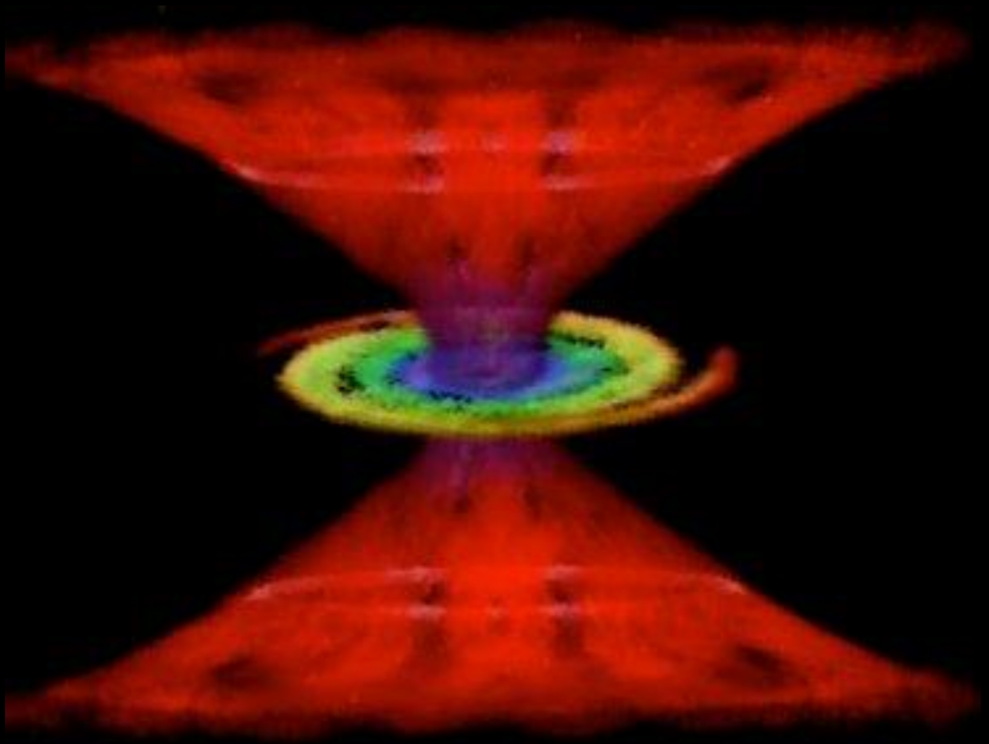


Martin Elvis proposed a unified model of quasar structure that accounts for seemingly contradictory spectral features observed in these objects. Astrophys. J. **545**, 63E (2000)

The three types of quasars are actually three different views of the same object

Quasar Structure

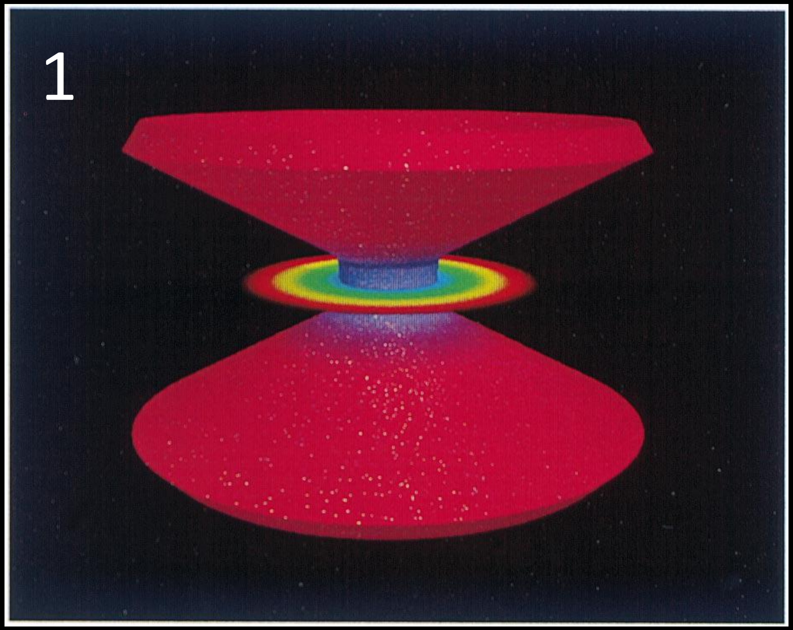
At the center of a quasar lies a black hole surrounded by an accretion disk. The central regions emit a continuum of radiation.

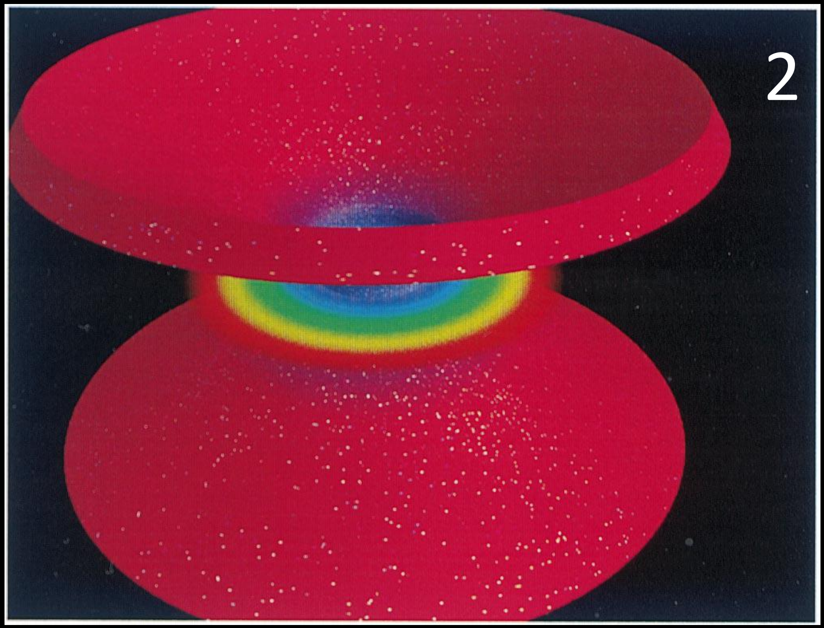


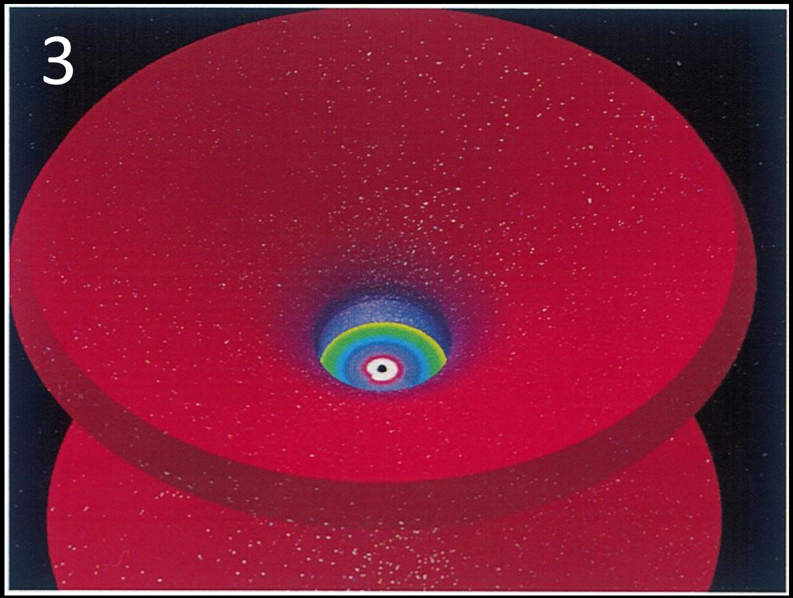
- A warm wind rises perpendicular to the accretion disk over a narrow range of radii.

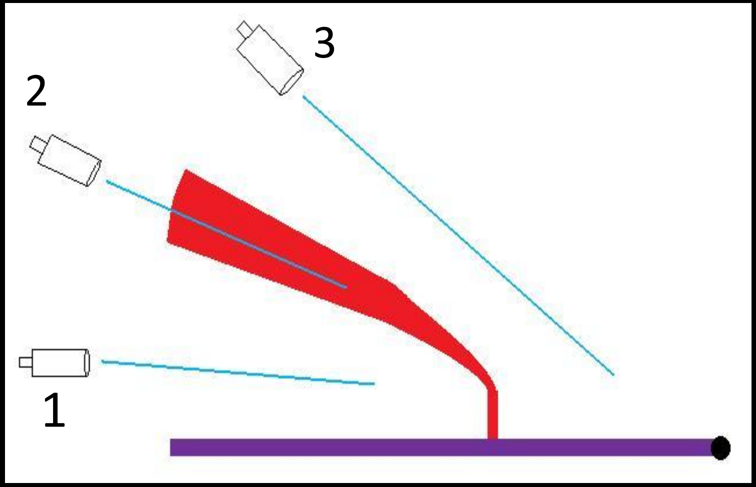
- The wind is accelerated by radiation pressure to form a funnel-shaped outflow.

Quasar Structure





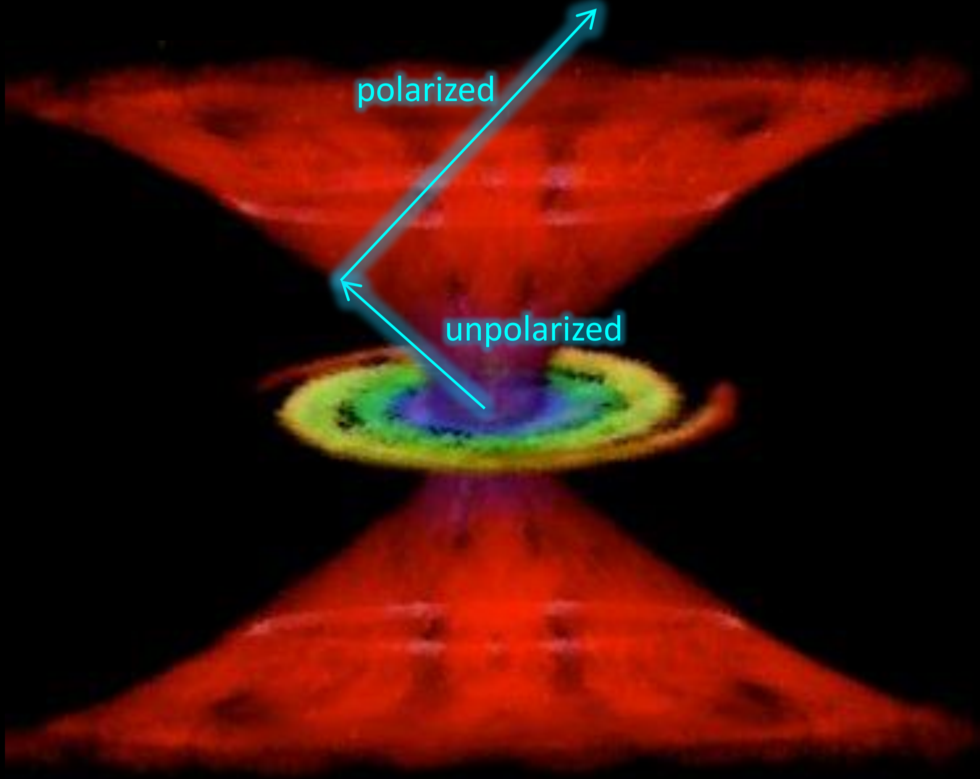




Elvis, Astrophys. J. **545**, 63E (2000)

Thomson Scattering In Quasars

Light becomes polarized from Thomson scattering: where a photon scatters of an electron.



Light emerges (unpolarized) from the central regions of the quasar.

The light is scattered of the hot gas of the funnel-shaped outflow and becomes polarized.

Remember that with BAL quasars we are looking down the outflow.

We observe the direction of polarization be parallel to the projection of the quasar axis on the sky.

Structure Formation In the Presence of a Background Magnetic Field

Magnetohydrodynamic equations are:

$$\rho\left(\frac{\partial\vec{v}}{\partial t}+\frac{\dot{a}}{a}\vec{v}+\frac{(\vec{v}\cdot\nabla)\vec{v}}{a}\right)=-\frac{\nabla p}{a}-\rho\frac{\nabla\phi}{a}-\frac{\left(\nabla\times\vec{B}\right)\times\vec{B}}{4\pi a}$$

$$\frac{\partial\rho}{\partial t}+3\frac{\dot{a}}{a}\rho+\frac{\nabla\cdot(\rho\vec{v})}{a}=0$$

$$\frac{\nabla^2\phi}{a^2}=4\pi G[\rho-\rho_b(t)]$$

$$\nabla\cdot\vec{B}=0$$

$$\frac{\partial}{\partial t}\left(a^2\vec{B}\right)=\frac{\nabla\times\left(\vec{v}\times a^2\vec{B}\right)}{a}$$

ρ = density
a = scale factor
$\vec{v}$ = peculiar velocity
$\vec{B}$ = magnetic field
ϕ = grav. potential
G = Newton's grav. constant
p = pressure

The Lorentz (magnetic) force induces overdensities $\delta\rho$(x,t velocities $\vec{v}$(x,t) in the smooth background fluid ρ_b(t). The backreact to induce an additional magnetic field $\delta\vec{B}$(x,t).

Structure Formation In the Presence of a Background Magnetic Field

Density:

$\rho(x,t) = \rho_b(t) + \delta\rho(x,t) \equiv \rho_b(t)[1 + \delta(x,t)]$

Magnetic field:

$\vec{B}(x,t) = \vec{B}_b(x,t) + \delta\vec{B}(x,t)$

$$\rho\left(\frac{\partial\vec{v}}{\partial t} + \frac{\dot{a}}{a}\vec{v} + \frac{(\vec{v}\cdot\nabla)\vec{v}}{a}\right) = -\frac{\nabla p}{a} - \rho\frac{\nabla\phi}{a} - \frac{(\nabla\times\vec{B})\times\vec{B}}{4\pi a}$$

$$\frac{\partial\rho}{\partial t} + 3\frac{\dot{a}}{a}\rho + \frac{\nabla\cdot(\rho\vec{v})}{a} = 0$$

$$\frac{\nabla^2\phi}{a^2} = 4\pi G[\rho - \rho_b(t)]$$

$$\nabla\cdot\vec{B} = 0$$

$$\frac{\partial}{\partial t}(a^2\vec{B}) = \frac{\nabla\times(\vec{v}\times a^2\vec{B})}{a}$$

Linearizing the MHD equations in small quantities $\delta\rho(x,t)$, $\delta\vec{B}(x,t)$, and $\vec{v}(x,t)$:

$$\frac{\partial}{\partial t}\left(a^2\delta\vec{B}\right) = \frac{\nabla\times\left(\vec{v}\times a^2\vec{B}_b\right)}{a}$$

ρ = density

ϕ = grav. potential

a = scale factor

p = pressure

$\vec{v}$ = peculiar velocity

$\vec{B}$ = magnetic field

G = Newton's grav. constant

Structure Formation In the Presence of a Background Magnetic Field

- ☞We are mostly concerned with the general behavior of the fluid.

- ☞We follow the evolution of $\vec{v}$ to zeroth order in δ and $\delta\vec{B}$.

Linearized Faraday's Law describes the evolution of the background B-field.

$$\vec{B}_b(\vec{x},t) = \vec{B}_b(\vec{x})e^{-2Ht}$$

Linearized Euler's Equation describes the evolution of $\vec{v}$.

$$\frac{\partial \vec{v}}{\partial t} = -\frac{\dot{a}}{a}\vec{v} - \frac{\nabla\phi}{a} + \frac{\mu_o}{4\pi a \rho_b}\vec{j} \times \vec{B}_b$$

ρ = density

a = scale factor

$\vec{v}$ = peculiar velocity

ϕ = grav. Potential

G = Newton's grav. constant

p = pressure

$\vec{B}$ = magnetic field

$\vec{j}$ = current

H = 2.3×10^{-18} s^{-1}

Structure Formation In the Presence of a Background Magnetic Field

$$\frac{\partial \vec{v}}{\partial t} = -\underbrace{\frac{\dot{a}}{a}\vec{v}}_{\text{Friction term}} - \underbrace{\frac{\nabla \phi}{a}}_{\text{Gravitational term}} + \underbrace{\frac{\mu_o}{4\pi a \rho_b}\vec{j} \times \vec{B}_b}_{\text{Magnetic term}}$$

To compare the relative strength of the gravitational term to the magnetic term, we define the ratio Ξ:

$$\Xi = \frac{\frac{4}{3}\pi G \rho_b r}{10^{-7}|B_b| v_\perp}$$

ρ = density

a = scale factor

$\vec{v}$ = peculiar velocity

ϕ = grav. Potential

G = Newton's grav. constant

p = pressure

$\vec{B}$ = magnetic field

$\vec{j}$ = current

H = 2.3×10^{-18} s^{-1}

Structure Formation In the Presence of a Background Magnetic Field

$$\Xi = \frac{\frac{4}{3}\pi G \rho_b r}{10^{-7}|B_b|v_\perp}$$

$\rho_b = 3.8 \times 10^{-28}$ kg/m^3

$|B| = 10^{-12}$ G

of a 10 K cloud located at $z = 9$

$\Xi_{H^+} = 80$/kpc

$\Xi_{e^-} = 1.9$/kpc

$\Xi_{H^+} = 2.46 \times 10^{-2}$/LY

$\Xi_{e^-} = 5.78 \times 10^{-4}$/LY

ρ = density

a = scale factor

$\vec{v}$ = peculiar velocity

ϕ = grav. Potential

G = Newton's grav. constant

p = pressure

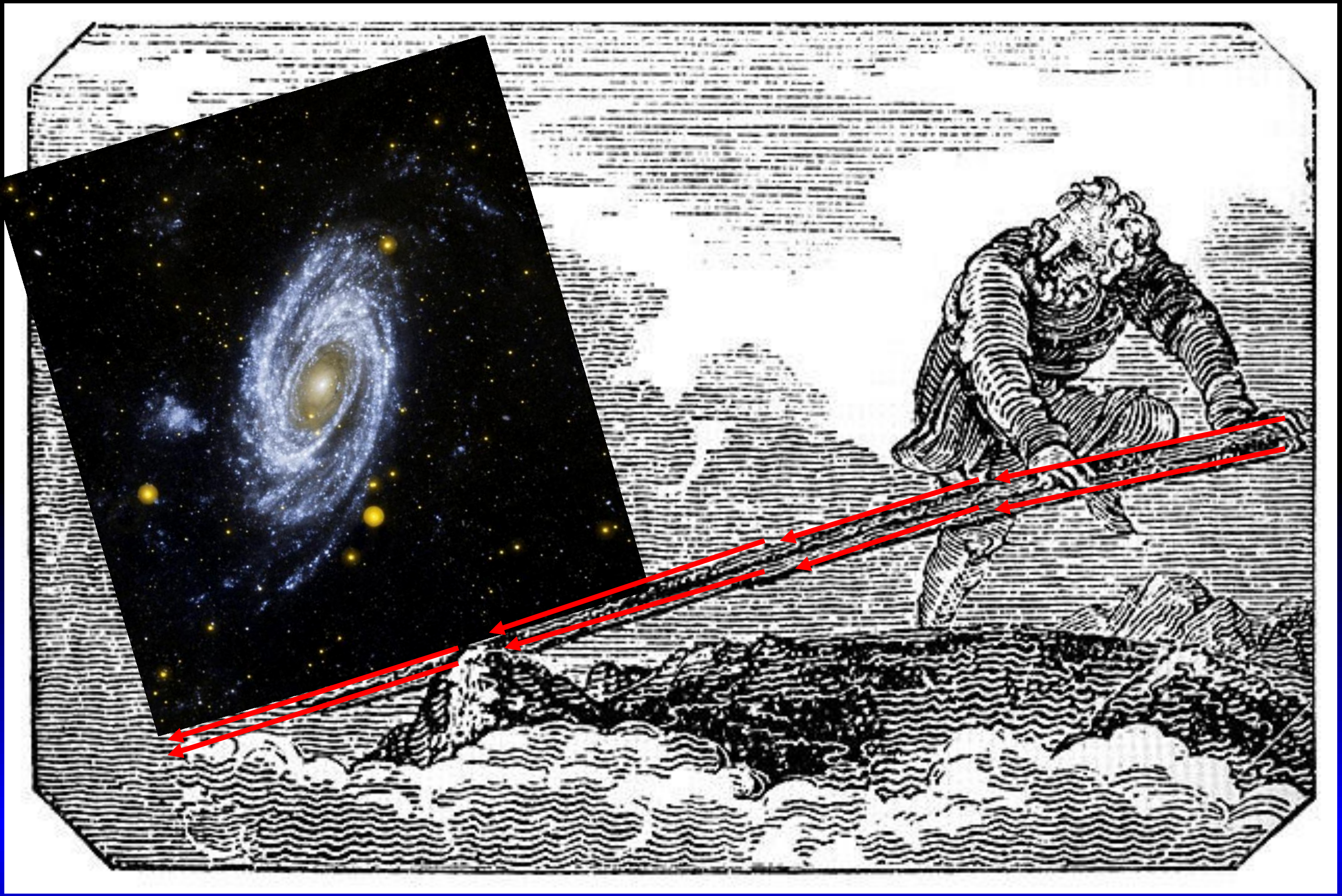
$\vec{B}$ = magnetic field

$\vec{j}$ = current

H = 2.3×10^{-18} s^{-1}

An Alternative Method to Align Quasars

“ΔΟΣ ΜΟΙ ΠΟΥ ΣΤΩ ΚΑΙ ΚΙΝΩ ΤΗΝ ΓΗΝ”



Give me a place to stand on, and I will move the Earth†.*

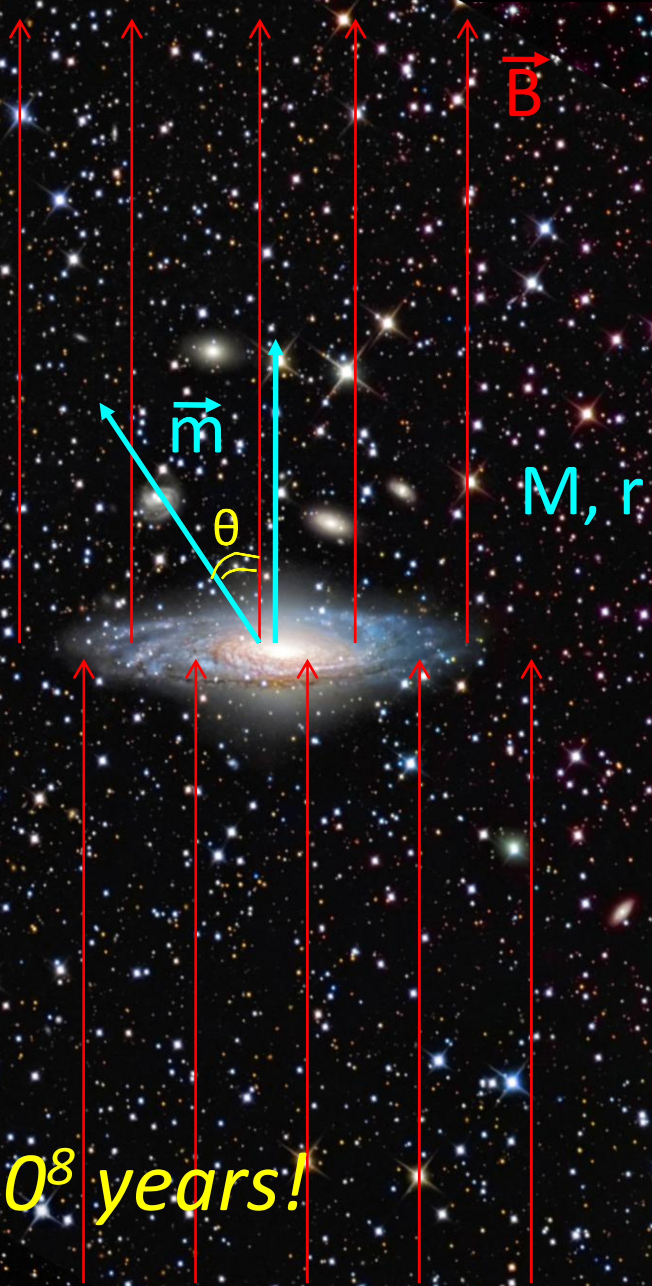
**Big enough magnetic field*

†a galaxy

An Alternative Method to Align Quasars

- Approximate a galaxy to be a solid disk
- The typical time scale to flip a galaxy is

$$\Delta t \sim \sqrt{\frac{2I}{mB}}$$



Using fiducial values:

$M \sim 10^{11}\ M_{\odot}$

$r \sim 15$ kpc

$B \sim 10^{-12}$ T

$m \sim 10^{63}$ J/T

The typical flip time is ~ *1.5 × 10^8 years!*

The Observation

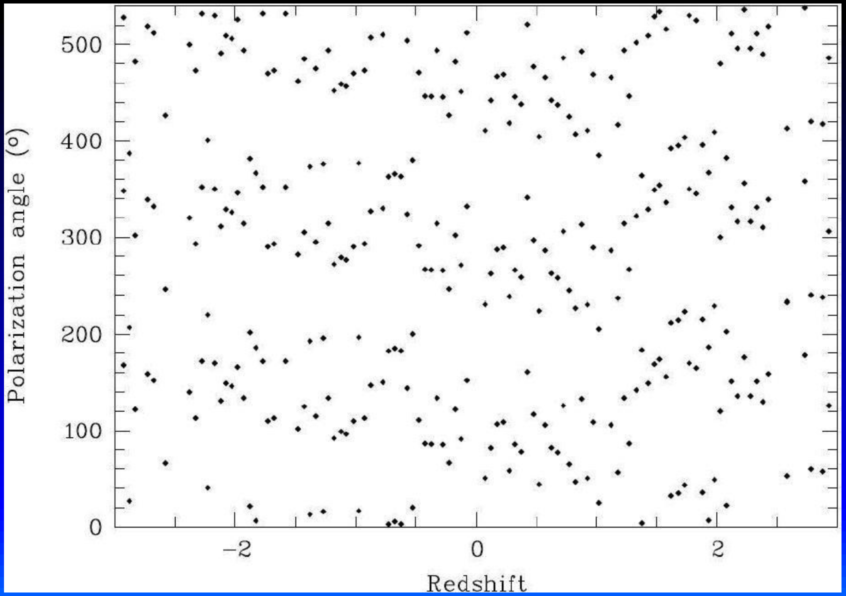
In 2005 Damien Hutsemékers, et. al. published linear polarization data of a sample of 355 quasars.

They noticed:

☞The direction of polarization of any given quasar is similar to the average direction of polarization of other neighboring quasars.

☞The average angle of polarization rotates with redshift.

The effect appears to be cosmological!



Hutsemékers, Cabanac, Lamy, and Sluse, Astron. Astrophys. **441**, 915H (2005)

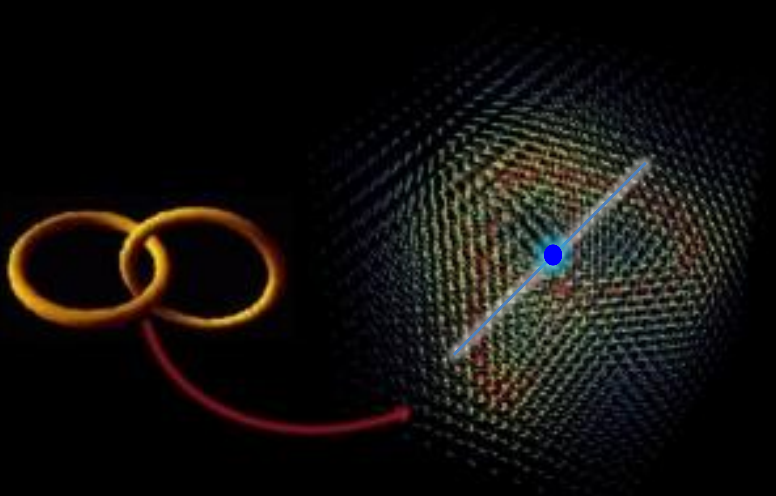
The Sample

- All objects were observed at high galactic latitudes ($|b|>30^o$)

- Certain objects that were given observational preference:

    - BAL quasars
    - Red quasars
    - Radio loud quasars
    - Quasars in two regions of sky where an alignment effect was previously observed

Matching the Model With Observation

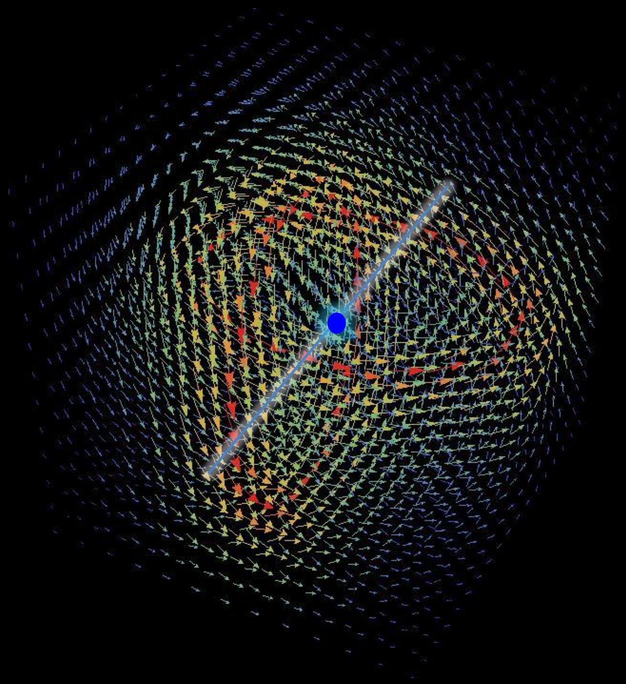


Magnetic field left over from two circular string loops of radius R separated a distance d

$$\vec{B} = \frac{B_o}{R}\Bigg[\left(-[y+d]\cdot exp\left[-\sqrt{z^2+\left[\sqrt{x^2+(y+d)^2}-R\right]^2}\right]\right)\hat{x}$$
$$+\left(x\cdot exp\left[-\sqrt{z^2+\left[\sqrt{x^2+(y+d)^2}-R\right]^2}\right]-z\cdot exp\left[-\sqrt{x^2+\left[\sqrt{y^2+z^2}-R\right]^2}\right]\right)\hat{y}$$
$$+\left(y\cdot exp\left[-\sqrt{x^2+\left[\sqrt{y^2+z^2}-R\right]^2}\right]\right)\hat{z}\Bigg]$$

We postulate the A1-A3 axis to lie roughly along the diameter shared by both loops.

Matching the Model With Observation



The y-axis of $\vec{B}$ is chosen to coincide with the A1-A3 axis.

The observed direction of polarization will be the direction of $\vec{B}$ projected onto the celestial sphere.

Along the A1-A3 axis:

$$\theta = \frac{180}{\pi}\tan^{-1}\left[\frac{(y+s+d)exp\left[-\big||y+s+d|-R\big|\right]}{(y+s)exp\left[-\big||y+s|-R\big|\right]}\right]+b$$

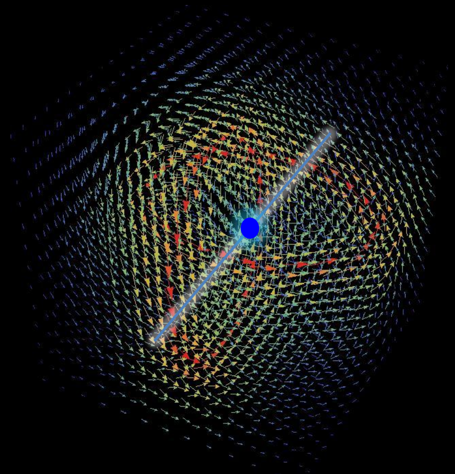
R = loop radius

s = shift along y-axis (A1-A3 axis)

d = separation of center of loops

b = shift in angle

Matching the Model With Observation



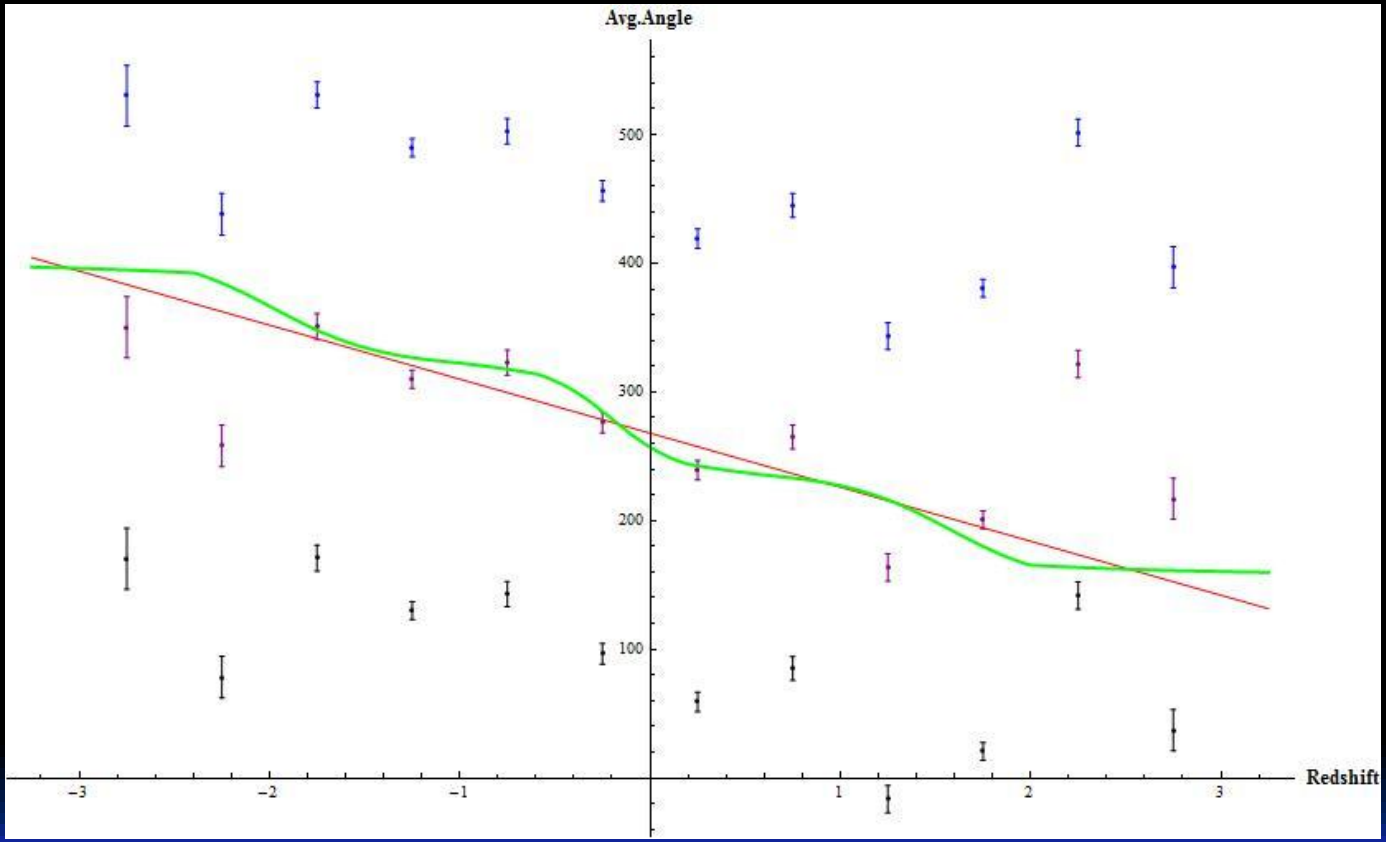
$$\theta = \frac{180}{\pi}\tan^{-1}\left[\frac{(y+s+d)exp[-||y+s+d|-R||]}{(y+s)exp[-||y+s|-R||]}\right] + b$$

Hutsemékers, et. al. propose a best fit of
θ = 268 – 42 z

Chi-square = 98.4

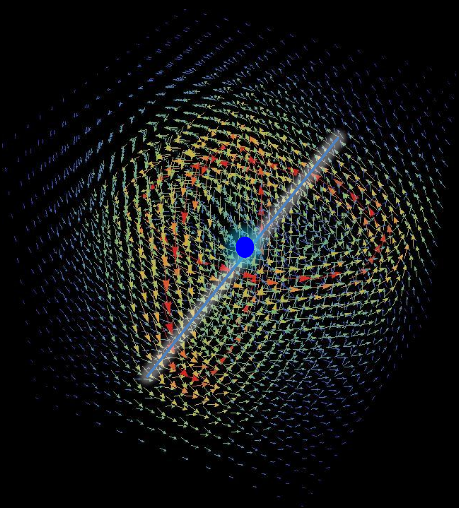
Our model:
S = -0.70 d = 1.80
R = 1.29 b = 324

Chi-square = 84.2



Average angle of the 183 quasars along the A1-A3 axis in bins of $\Delta z = 0.5$
Error bars show the 68% angular confidence interval.

R = loop radius
s = shift along y-axis (A1-A3 axis)
d = separation of center of loops
b = shift in angle



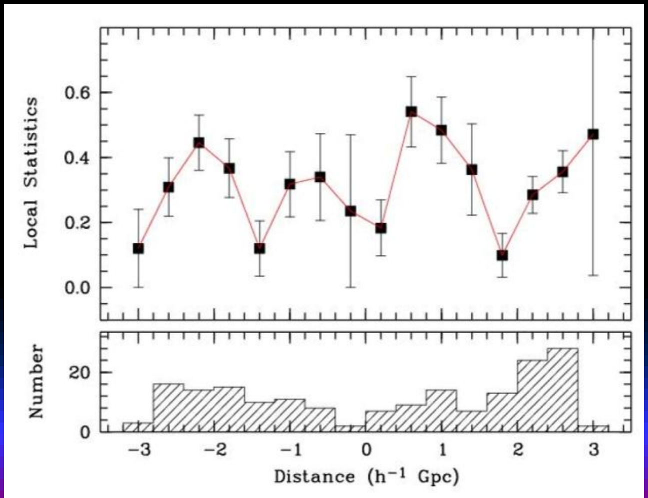
Matching the Model With Observation

Highest degree of alignment should occur in regions near the magnetic field loops.

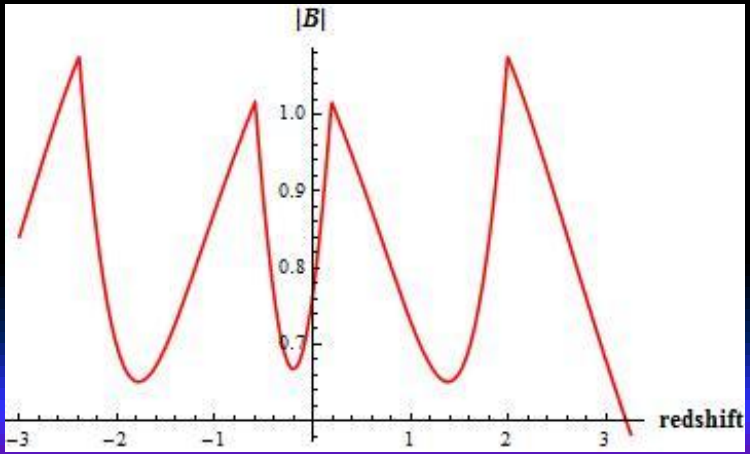
Dropoff in the degree of alignment:

 Far away from the field loops

 Regions where the magnetic field direction becomes parallel to our line of sight

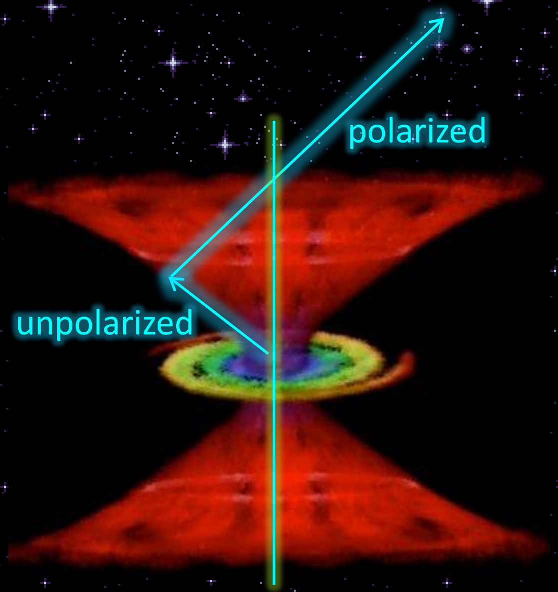


Hutsemékers, Cabanac, Lamy, and Sluse, Astron. Astrophys. **441**, 915H (2005)



Conclusions

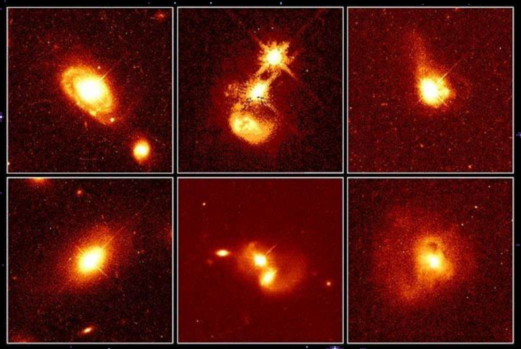
- Hutsemékers, et. al. made two observations that are difficult to accommodate in simple ad-hoc models:



- Large-scale alignment
- Coherent rotation

The direction of optical linear polarization is related to the physical orientation of the quasar itself.

Knowing the direction of polarization allows us to know the physical orientation of the quasar itself.



Conclusions

Magnetic fields can affect structure formation.

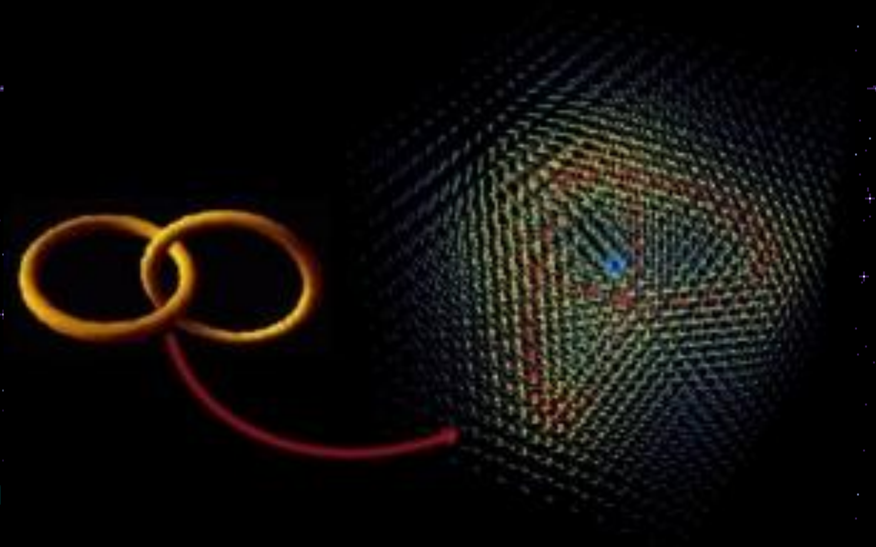
A background magnetic field

Will impart a preferred direction to a collapsing (protogalactic) cloud

May cause a torque on a disk, favoring the disk to align with the background B-field

These two effects work synergistically together.

Conclusions

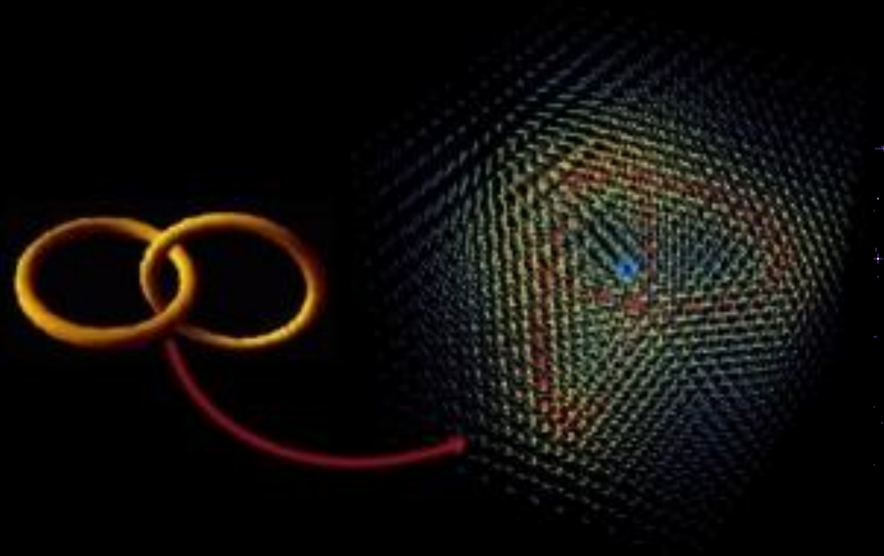


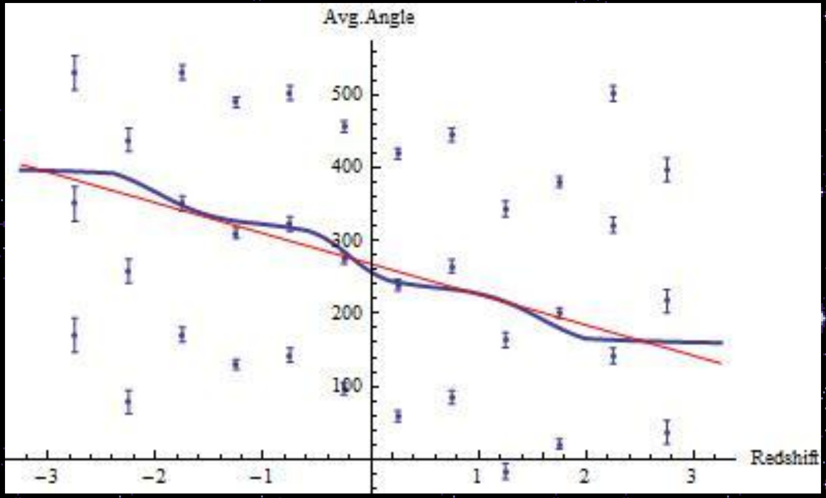
- The geometry of two interlinked strings explains the observed rotation through ~ 250º very well
- The initially small magnetic field loops are carried by the expansion of the universe…today they exist on cosmological scales!

- Because strings contain wiggles, we do not expect the loops to be perfectly circular.
- We still expect to see certain trends in the data

Conclusions

- Our model explains both the large-scale alignment and coherent rotation of quasar polarization vectors…





- …without resorting to exotic physics or non-standard cosmology…
- …and is very testable (falsifiable).

Thank you to my collaborators
Dejan Stojkovic and De-Chang Dai

Thank you!